NEW APPROACHES FOR COMPUTER-BASED CONSTRUCTION PROJECT PLANNING

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ABSTRACT: The paper reviews the principles of existing computer-based planning tools, and proposes a syntheses of many of these ideas, along with some enhancements. The overall aim is to provide a single tool that embraces the advantages of each of the current planning methodologies, and that is better suited to the demands of present-day construction project management. The specific objectives of the tool are simplicity in use, versatility in application, provision of user insight into the functioning of a project, and effective optimization of the project objectives. At the functional level, the developments are concerned with: (i) the way in which a model is structured (simplifying model design and understanding); (ii) redefining the way in which tasks interact and depend on each other (so that the approach is no longer limited to a schedule-centric perspective with interactions occurring at discrete points in time); (iii) providing a more realistic representation of resources and their dependencies to reflect the way work may actually be carried out on site (such as the use of flexible and divisible crews); (iv) the visualization (graphic representation) of both the model structure and work progress within an integrated format that also facilitates model development and editing; and (v) optimization of the overall project objectives. The principles of the existing and proposed new approach to project planning are discussed and rationalized, and application of the new approach is demonstrated and compared to existing planning methodologies for some example construction processes.

KEYWORDS: project planning; project optimization; critical path method; hybrid continuous-discrete simulation; linear projects.

1 INTRODUCTION

The evolution of construction planning tools is illustrated by Figure 1, showing the genealogy and timeline of the most familiar of these tools. An open circle in this figure represents the emergence of a planning tool that is either in itself new or at least introduces a new modeling concept (such as Gantt Charts, or 4D CAD (see for example Koo & Fischer(2000)). The solid lines show the ancestries of the different tools, while the dashed lines with dots show where new modeling features are introduced to an existing planning tool (these features are often ideas taken from other planning tools). The figure shows clearly that there has been a fairly consistent expansion in the number of tools over the last 100 years, and that while there has been some cross-fertilization of modeling concepts, there is no single tool that fully integrates ideas across the spectrum.

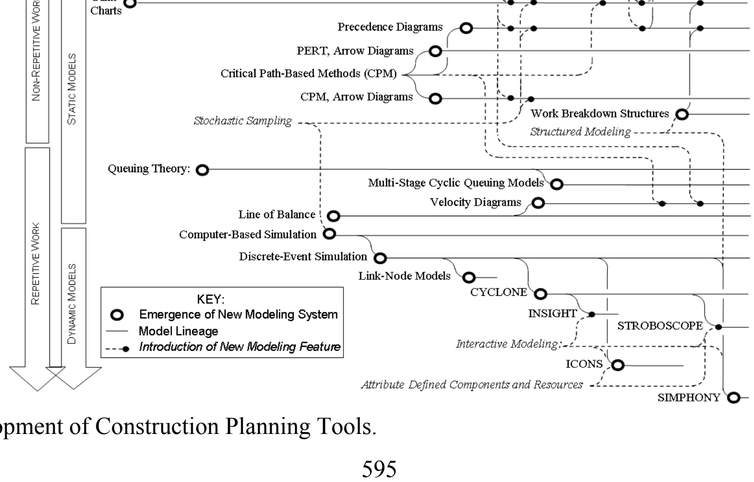

Figure 1. History of Development of Construction Planning Tools.

The split arrows to the left of this figure identify two dichotomies. The first divides the tools into those used to model repetitive construction work and those used to model non-repetitive work. The second dichotomy divides the tools into those that are dynamic (which is predominantly simulation methods (Halpin & Woodhead,1976), (Sawhney et al., 1998), (Hajjar & AbouRizk, 2002)) and those that are static (such as the critical path-based methods - CPM).

Linear scheduling methods (see for example Matilla and Abraham (1998)), are an example of static modeling tools used for planning work that is repetitive or that can be reduced to a set of repetitive tasks. It has long been noted that the tools classified as static and targeted at non-repetitive construction work (such as the CPM-based tools) are not very good at modeling construction work that is repetitive in nature (such as tunneling or high-rise construction) (Harris & Ioannou, 1998). When applied to repetitive work, these tools generate models that are unduly complicated and provide little understanding of the interactions between repetitive construction tasks. On the other hand, while the dynamic models are very versatile at representing repetitive work, they are not particularly easy to use, and are unnecessarily complicated and not very insightful when it comes to modeling non-repetitive work. The static modeling techniques targeted at repetitive work (such as linear scheduling) are very easy to understand and provide great insight into the behavior of a construction system, but they cannot be used at all to model non-repetitive work and include some simplistic assumptions which often make it difficult to model real-world repetitive work. Velocity diagrams, for example, cannot easily represent operations that use flexible crews, that is, crews that may be split-up occasionally to work temporarily on several tasks and then regrouped later (which is often the way they are utilized in repetitive working environments).

Regrettably, there is no single tool well suited to modeling the broad spectrum of repetitive and non-repetitive construction work in terms of versatility, insight, and ease of use. Thus, planners are left with two choices: (i) to use a selection of planning tools or; (ii) to use a single tool for planning all types of work even though it will not always be the most appropriate. The first choice is rarely adopted since it requires the planner, and all other involved parties, to be proficient in the use of several software packages some of which they may only use on rare occasions; moreover, the results from the different tools cannot be readily integrated into a single analysis. Most often, a critical path-based method is adopted and applied to all situations, compromising modeling of the repetitive elements of a project.

Another issue is that the principles upon which these tools are based are often flawed or biased towards a view of planning that is out dated. The critical path method, for example, has a time-centric view of planning, and treats other parameters and constraints very much as secondary issues – as a result, distance buffers between concurrent linear tasks must be converted into a time equivalent (which is misleading and un-insightful).

This paper goes back to basics and attempts to develop a new modeling paradigm that is relevant to all issues in contemporary planning and applicable to all types of construction project.

2 STRUCTURED ACTIVITY MODELING

The first precept in the proposed approach to project planning is the adoption of a strongly structured view of the work involved in a project. Structured modeling has long been recognized in systems science as a powerful way of developing and defining representations of very large and complex systems. In essence, a structured approach forms a representation of a system by decomposing it into categories of tasks and subtasks, in a top-down manner. For construction, the decomposition into tasks should be building-component oriented (as opposed to say material-type, or trade oriented) since this reflects the way in which buildings are assembled. The main advantages of a structured approach to modeling are simplified model development and revision, fewer errors in the model design, and better insight into the system being modeled (since the model provides understanding at different levels of abstraction) (AbouRizk and Hajjar (1998), Huber et al. (1990), Ceric (1995)).

The basic concept of structured modeling is already adopted in construction project planning in the form of Work Breakdown Structures (WBS's) and is even implemented in some project planning software packages. WBS's are, however, simply a classification or grouping of work tasks (to make the model more readable) and are not an integral part of the structure and operation of the model, that is, they do not help define the logic of the model or its constraints.

Consider for example, the sample project plan shown in Figure 2. The left side of the figure shows the project organized within a conventional WBS format, while the right side shows the equivalent project organized using a fully structured approach. For both approaches, each block represents a task (or sub-task) and each link represents a dependency (timing for most planning models) between tasks. A fundamental difference, however, is that the structured approach allows the dependencies to be defined between tasks at any level in the network (the scope of dependency of a link being all sub-tasks within the task to which it is connected) whereas the WBS approach requires all logic to be defined at the lowest level tasks. In this example, the Tasks 1.3.1 and 1.3.2 require Tasks 1.1.2 and 1.1.3 to be completed, and Task 1.3.2 requires additionally Task 1.2.2 to be completed. Clearly, the structured approach reduces the total number of links required to define the logic, thus making the plan easier to read and modify. Also, more subtly, the structured approach provides a better insight into the logic of the project by indicating generalized relationships (those at higher levels of abstraction). For example, it is clear from the structured format that the high-level component represented by Task 1.3 is fully dependent on the completion of the high-level component represented by Tasks 1.1, and partially dependent on completion of Task 1.2.

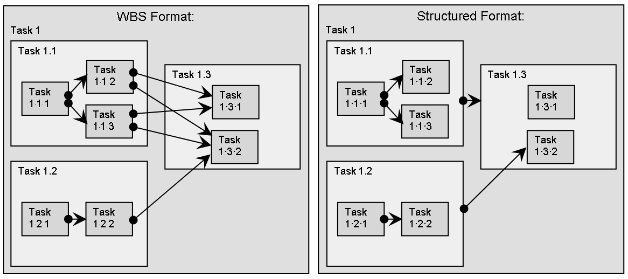

Figure 2. WBS versus Structured Approach to Network Representation.

Interestingly, a computer-based implementation of this approach could readily determine the simplest set of structured links that would achieve a given logic. Thus, a planner may input links at an unnecessarily low level in the structure (in an extreme case, this would be to input all links at the lowest level tasks) and the software would reduce these to the minimum set of higher-order links. Moreover, the computer implementation could be readily programmed to identify and suggest new groupings of tasks that would further reduce the number of links (such as illustrated by the dashed boxes in Figure 3) – such groupings may have some physical meaning and value in the organization of the project that the planner had not previously identified, in addition to enhancing the readability of the model's logic.

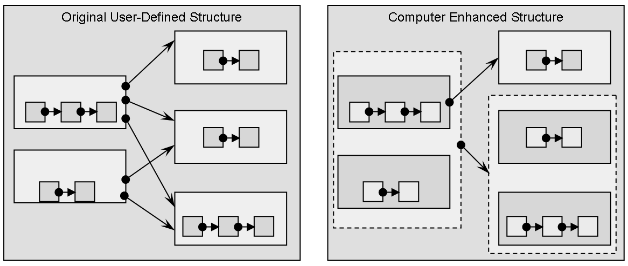

Figure 3. Computer-Based Optimization of Project Structure.

3 MODEL CONSTRAINTS AND FREEDOMS

The progress of work on a project is partially determined by constraints on the system. The constraints are any logical requirements that must be satisfied, and range from limitations on the availability of resources (equipment, money, space, etc) through to a requirement for one task to maintain a minimum amount of work in advance of another task (a distance or time buffer for example). Any planning methodology must allow all significant constraints to be taken into account.

In contrast, all projects have a number of freedoms in the way in which work may be executed. For example, some tasks may not be able to occur at the same time but might have the freedom to be executed in any sequence. Other tasks may have some leeway in terms of the numbers of resources they need to perform the work, such as flexible crews where all members may work together on a single task for a while and then later split to perform concurrent tasks. The freedoms in a project create the need for optimization; that is, determining the choice from within the freedoms that will satisfy the project objectives most effectively. For the proposed system, optimization of a project plan would make use of Genetic Algorithms, due to the ability of these techniques to handle problems that comprise both discrete and continuous parameters and complicated system structures and dependencies.

3.1 *Task dependencies*

Dependencies between tasks (that is, where the progress of a tasks is limited in some way by the progress of other tasks) is the most common form of constraint considered in planning. Figure 4 illustrates the different methods used for defining task dependency between two continuous processes using: (a) precedence networks; (b) simulation diagrams; and (c) velocity diagrams. In the precedence network approach (see Figure 4(a)), the arrows indicate event dependencies between tasks, typically used to indicate that the preceding task must finish before the successor task can start. Less commonly, the dependencies may be between the start events of both tasks, the finish events of both tasks, or even the start event of the preceding task and the finish event of its successor. Also, in a precedence network, each task is executed just once.

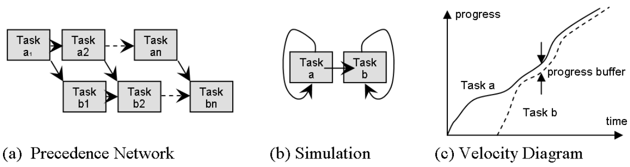

Figure 4. Representation of Dependencies for Three Common Planning Tools.

For most simulation methodologies used in construction, the arrows in a diagram show the flow of resources between tasks, indicating that a task cannot start until some combination of resources are available at its input (typically with either an AND logic or an Exclusive-OR logic). Task 'b' in Figure 4(b), for example, requires some combination of resources from both tasks 'a' and 'b' in order to be functionally the same as the precedence network. In contrast to the precedence network, the simulation approach allows tasks to be repeated many times, possibly by different resources performing the task concurrently.

For a velocity diagram (such as that shown in Figure 4(c)), the dependence between tasks is imposed by a buffer between the respective progress curves. The buffer can be time oriented (giving a minimum advance in time that must be maintained by the preceding task over its successor), or it may be progress oriented (giving a minimum advance in quantity of work that must be maintained by the preceding task over its successor) as shown in this figure.

Each of the above three approaches has its own advantages. The precedence network approach is very simple to use, but is not well suited to projects where many of the tasks are repetitive in nature. Simulation is the most versatile allowing relatively complicated logical dependencies to be developed between tasks, but these dependencies are limited to discrete task events. The velocity diagram approach is simple to understand and allows continuous dependencies between the progress of tasks, but it lacks the versatility of the simulation approach and requires all tasks to operate along a single sequence.

Ease of use and versatility (which in turn impacts accuracy) in modeling are key attributes for any planning tool. In the case of task dependencies, this balance can best be achieved using an extension of the velocity diagram technique. For the proposed system, dependencies can be defined between any tasks (and at any level) that limit their relative progress, and for any measure of work (time, distance, units completed). The advance in progress may be specified to be above or below a given value, and their may be more than one such dependency between two tasks. Thus, it may be defined that task ‘A’ be at least 10 m behind task ‘B’ but no more than 25 m behind. Another variant would be for the progress of the tasks to flip-flop between the limits so, for example, task ‘A’ may operate until it is 25 m ahead of task ‘B’ but then wait until task ‘B’ catches up to 10 m distance. This approach has the versatility to model any dependency available in the precedence network, velocity diagram, and the commonly used simulation diagram approaches. Figure 5 compares the proposed representation with that of the CYCLONE system (Halpin and Woodhead (1976)) for a concrete production and distribution system. The system represented comprises a 1 cu-m concrete batching plant, a 5 cu-m hopper for storing wet-concrete, and two 10 cu-m distribution trucks. In the proposed new approach (part (b) of the Figure), most of the dependencies would simply specify that preceding tasks must be completed before their successors can start. However, the link between the middle-level tasks would specify that ‘Concrete Production’ must be between 0 and 5 cu-m of wet concrete ahead of ‘Concrete Delivery’. This would impose the logic of a 5 cu-m wet-concrete hopper between these middle-level tasks, equivalent to that of the CYCLONE model.

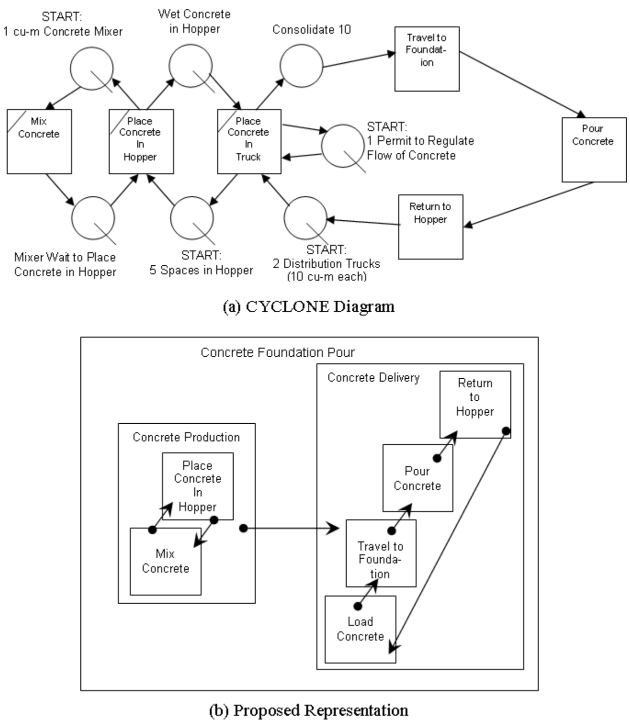

Figure 5. Concrete Foundation Pour.

3.2 *Structured resources*

The second primary class of constraint in a project (following task dependencies) is that of resource availability (equipment, labor, space, materials, work completed, money, etc). In the proposed system, a structured approach to defining resources is adopted (similar to that for defining the tasks) in that a resource may comprise several sub-resources and sub-sub-resources. Each resource, or sub-resource, may be defined as an actual quantity required to complete a task or it may be defined as a range of values. The range of values provides a degree of freedom within the model creating an opportunity for project optimization, and facilitates consideration of factors such as flexible crews – for example, the number of general laborers in a crew may be allowed to vary within a specified range and thus crew members would be able to drift between tasks on an as-needs basis.

4 VISUALIZATION OF PROJECT DEVELOPMENT, PERFORMANCE, AND STRUCTURE, WITHIN AN INTEGRATED ENVIRONMENT

4.1 *Visualizing progress at multiple levels*

Visualization of progress in a project is essential to understanding the effectiveness of a given plan, understanding the actual progress of work on site, identifying possible problems (and their ramifications), and proposing solutions to problems that will satisfy the project objectives. While precedence diagrams and simulation diagrams are useful for understanding the work involved in a project and the dependencies between tasks, the velocity diagram provides the most insight into the impact of task relationships on project progress. Velocity diagrams can, incidentally, be produced as output from simulation models. Precedence diagrams can (following a time analysis) be used to generate project progress curves, but these plots do not associate progress with the individual tasks, and thus provide limited visual insight into the impact of those tasks on the performance of the project.

The structured view of a project plan in the proposed approach enables visualization of progress at many levels of detail and in a format similar to that of velocity diagrams. The project task structure can be graphed to scale with, for example, time shown in one direction and some measure of progress (such as cost or activity-days) plotted in the second direction. An example of this is provided in Figure 6 for part of a plan for an office complex. Progress is plotted in this scaled manner within each task box (cost versus time), and these task boxes can be peeled away to view progress at the higher levels in the project. This way, a user can, in an interactive environment, explore project progress at all required levels of detail. In this example, since cost can be integrated, each higher level box can show a summary of the cost accumulated from all lower level boxes.

For sections of the project that are linear in nature (such as pipeline construction, tunneling, or highway construction) where several tasks follow each other on the same section of the project, the progress plots would result in something very similar to a velocity diagram. This is illustrated in Figure 7 which shows a structured model of the planned construction for the concrete structural system of a medium-rise apartment block. All boxes in the hierarchy measure 'time' in the horizontal direction. The outer level box measures 'floor level' in the vertical direction, the third level boxes measure 'square footage' in the vertical direction, and the fourth level boxes measure, for example, 'square footage' (for 'forms'), 'tons' (for 'reinforcement'), and 'cubic yards' (for 'pour concrete'). While these variables may seem incompatible and thus cannot be plotted together, the implication is that there is a linear mapping from one variable to the other, scaled to the scope of the work represented by each box. A non-linear mapping could also be defined between two variables if the additional accuracy was considered necessary. The slight acceleration in the progress curves is the result of learning that the contractor had estimated for this project.

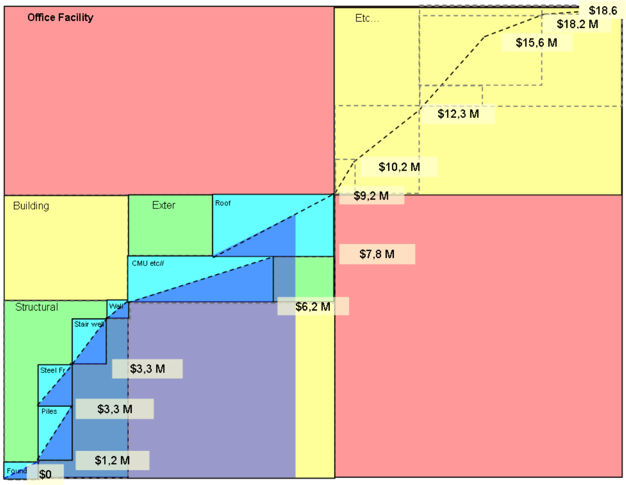

Figure 6. Structured Visualization of Progress of Work (Planned and Actual) for Part of an Office Construction Project.

While Figure 7 has many similarities to a velocity diagram, there are also some important differences. Most importantly, the model sits within a structured format, allowing the project to be viewed at different levels of abstraction. The different levels can be peeled away and a summary of progress at higher levels can be observed. Secondly, unlike velocity diagrams, different tasks may use different measures of progress. Other differences, not shown in this example, may include the use of flexible crews that move between tasks.

4.2 *Visualization and interactive model development*

The proposed modeling methodology involves task interactions that are sufficiently complex that a simulation algorithm is required to compute progress. A problem with conventional simulation methodologies is that the entire model must be defined before the simulation can be executed and the estimated progress can be plotted. However, the proposed structured modeling system does not suffer from this problem. Indeed, it is the intention that these structured models are built in an interactive environment where the impact on progress of adding each new component is viewed immediately. This is made possible by the structuring of the model, which enables development of a model in discrete units (the boxes) which can be resolved individually as they are added to the model. If a box at a high level in the model is added initially without its sub-boxes, its performance can still be generalized from its context in the model, and then refined when its sub-elements are added.

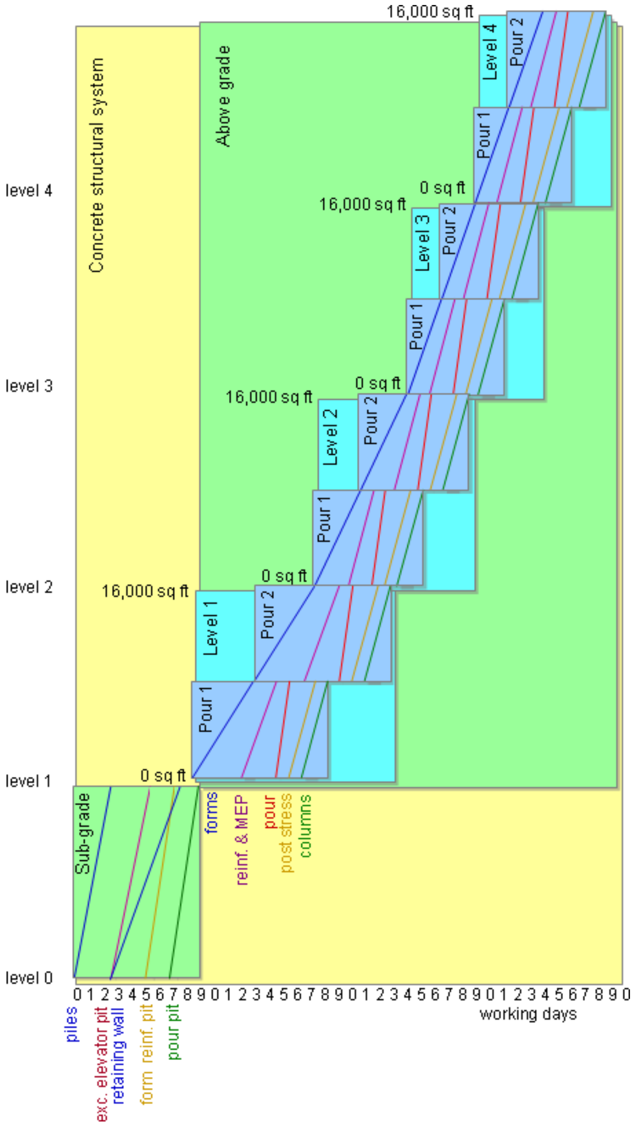

Figure 7. Structured Model of Medium-Rise Concrete Structural System.

There are many advantages to this approach, the first of which is that it allows a planner to debug and validate the model as each new element is added, since the consequences of an addition are immediately visible. For a similar reason, the approach facilitates optimization of the model by the planner who, in addition to being able to see the model logic and performance in an integrated framework, can also see the results of any changes/additions made to the model at the instant they are implemented. Thus, the planner can refine the model (as far as optimizing its performance objectives are concerned) during the initial development phase.

For repetitive (or partially repetitive) construction work, development and validation of the model is further simplified since the planner only needs define and debug one repetition of a component. For example, in Figure 7, the planner only needs to define the box representing construction of the first floor structural system and its dependencies with the second floor. The work represented by this will then be duplicated as many times as required. If any floor deviates at all in structure, then the box representing this work can be subsequently edited as required.

The structured approach is also conducive to visualization of a project utilizing the ideas of 4D-CAD whereby a facility and its construction progress can be viewed within a dynamic walk-through environment. This is made possible since the task-structure is component-oriented with each task representing a physical part of the building (at different levels of detail), and therefore has a one-to-one relationship with the architectural plans. Indeed, many 3D-CAD systems now enable designers to implement the design in a hierarchical framework as such (Issa et al. (2003)) and would thus be conducive to integration into a 4D-CAD environment using the proposed planning methodology.

5 CONCLUSIONS

The paper has outlined a new approach to project planning and control built on principles more pertinent to contemporary project planning. It recognizes the need to facilitate planning of very large and complicated projects, achieving this by means of a truly structured representation of work, and an integration of project structure and progress in a single representation. At the same time, it moves away from a time-centric view of project planning, allowing project constraints and freedoms (and thus project optimization) to be defined for all key project parameters.

Work is on-going developing detailed project plans using this system for a variety of project types, including underground utilities operations (water pipelines, sewers, gas pipelines, and electrical conduits) for large residential projects, high-rise condominium projects, and medium-rise office facilities. The objective of these studies is to determine the successes and limitations of the proposed planning method in the real-world, and to determine refinements that will increase its value as a planning tool.

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